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Experiments on an externally forced free shear layer are performed which study the origin of three-dimensional structures and chaos in shear flows. Transition routes between the laminar two-dimensional stages of shear flows and their final complex three dimensional stages are examined. Two avenues of investigation are pursued. First, the general idea of a multi-frequency route to chaos is examined which treats the shear flow as an open dynamical system. An attempt is made to apply concepts from nonlinear dynamics to these systems Secondly, a new approach to generating three-dimensional structures in shear flows which involves the creation of a spatial shear in the frequency of external perturbations is presented. In these experiments, a variety of vortex reconnection behaviors is observed at the discontinuity.

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FINAL REPORT ON THE

STUDY OF THE ORIGIN OF THREE DIMENSIONAL STRUCTURES AND CHAOS IN AN EXTERNALLY FORCED FREE SHEAR LAYER

INTRODUCTION

The problem of transition from laminar to turbulent regimes in shear flows continues to play a central role in research aimed at improving aerodynamic characteristics of fluid mechanical systems. Despite the success of linear theories in revealing the nature of the initial stages of instabilities, there remains a deep gap in understanding the connection between the non-linear stages of these two-dimensional waves and the development of the complicated three-dimensional phenomenon of turbulence. The heart of the problem is an understanding of the origin of secondary and higher instabilities which will ultimately result in the generation of turbulent spots in boundary layers or streamwise longitudinal vortical structures in mixing layers.

Two directions have been seen in previous investigations that attempt to relate the non-linear stages of the initial instabilities to the three-dimensional turbulent structures. The first concerns the development of finite amplitude oscillations (natural or externally forced) and involves linear or weakly non-linear, single frequency disturbances. The second approach concerns the understanding of the causes of spanwise modulation of waves shear flows.

Along the lines of the first direction of research, attempts have been made to explain the transition from laminar to turbulent flow in terms of ideas from the relatively new field of nonlinear dynamics. In particular, the concept of chaos has been studied extensively. Chaotic systems have the interesting property that they produce essentially unpredictable behavior even though the governing equations of motion are deterministic. Such is the case for the phenomenon of turbulence which could be considered to be the ultimate form of chaos.

Many examples of chaotic behavior have been observed in fluid mechanical systems whose governing equations (the Navier-Stokes equations) are nonlinear due to the presence of the advection terms. The most extensive documentation of chaotic behavior in hydrodynamic systems exists for two experiments**: Rayleigh-Bénard convection and Taylor-Couette flow which are examples of fully bounded (closed) flows. Closed flows are identified by the fact that a particle in the flow retains a history of its location in the system over all cycles of motion. In an open system (e.g., a water tunnel or channel), the particles are redistributed after each cycle. The location of a particle in one cycle is completely uncorrelated with its position in the next cycle. In other words, the velocity profile at the entrance to the open system test section is relatively uninfluenced by downstream events. In addition, closed systems contain significantly less background noise than open systems.

** For an extensive list of references on these flows, see Gollub & Benson[1] and Swinney[2].

Early studies of chaos in open flows focused on the wake of a thin cylinder[3,4]. More recently, in a series of fully controllable experiments on the wake of a thin airfoil[5], we have shown that the interaction of multiple frequencies can lead to chaotic behavior which plays a role in the transition to turbulence.

The second approach to the transition problem focuses on the development of three-dimensional structures in shear flows. The majority of shear layer studies in this area have used passive means to generate three-dimensional structures[6-8]. Of the studies that involve active forcing techniques, the primary control parameter is the phase variation of a disturbance across the span of a model[9,10].

In recent work on the wake behind a vibrating wire, Gharib*et al.* [11] showed that large scale structures can be generated as a result of a nonuniformity of vortex shedding frequency along the span of the wire. It is conjectured that the frequency variation along the span is the main contributor to cell structure in the wake of a cone[12].

The research described in this report involves the introduction of perturbations to a two-stream mixing layer (also referred to as "shear layer") to gain a better understanding of the transition process. The strip heater technique with various configurations for the strips are used to generate the perturbations. The paper will be divided in two parts. Part I examines the general idea of a multi-frequency transition route to chaos which treats the shear flow as a an open dynamical system. Part II examines a new approach in generating three-dimensional structures in mixing layers which focuses on the effect of a discontinuity in the vortex roll-up frequency along the span of the mixing layer.

OBJECTIVES

The objective of our research is to gain a better understanding of the non-linear pre-transitional process by introducing external perturbations to a two-stream mixing-layer. The strip heater technique with various configurations for the strips is implemented.

The primary objectives of the research are:

A. To examine the general idea of a multi-frequency transition route to chaos which treats the shear flows as open dynamical systems.

B. To examine a new approach in generating three-dimensional structures in the boundary and mixing layers.

EXPERIMENTAL PROCEDURES

The experiments were performed in the UCSD department of Applied Mechanics & Engineering Sciences water tunnel. The water tunnel has an 8 foot long test section with a 10" square cross section. To create the mixing layer, a splitter plate was mounted at the entrance to the test section. A velocity ratio of 2.6 was obtained using this technique.

Perturbations (waves) are introduced to the splitter plate boundary layers through the use of the strip heater technique[13] (fig. 1). The waves are amplified by the boundary layers and introduced to the shear flow. Due to the quadratic joule heating effect, each frequency must be input on a separate strip. Thus, to introduce several frequencies to the system simultaneously, multiple independent strip heaters were used. In order to create a discontinuity in frequency across the span of the mixing layer for part II strip heaters were mounted side by side along the span of the splitter plate (fig. 2).

Flow velocities were measured with a laser Doppler anemometer. The Reynolds number based on the shear layer thickness was approximately 1000 for most cases.

SHEAR FLOW RESPONSE

When forcing a system, it is necessary to establish the range of frequencies which will be amplified by the system. Figure 3 shows the response amplitude of a forced frequency (f_0) as measured in the shear layer. The most amplified frequency is close to the natural vortex roll-up frequency. In addition, the response of the subharmonic ($f_0/2$) and the second harmonic ($2f_0$) of the forcing frequency are plotted. When forced at f_0 away from the natural frequency, responses at either $f_0/2$ or $2f_0$ were observed if the sub- (or second) harmonic was near the natural frequency (fig.4). It was observed that the flow locks to the forcing frequency over a range of frequencies near the most amplified frequency.

DISCUSSION AND RESULTS - PART I
THREE FREQUENCY ROUTE TO CHAOS

In the case of single frequency forcing, the main parameters varied were the amplitude and frequency of forcing. By fixing one of the parameters (e.g. the amplitude), the effect of the second parameter was determined by sweeping it over a range of values. This type of procedure led to the results of receptivity and locking ranges. With the addition of more frequencies, the behavior of the system becomes increasingly complex as the frequencies interact. A sampling of behaviors observed in the shear layer is presented here. For each case, the autocorrelation function and the power spectrum associated with a representative time series is presented.

Before examining any forced cases, it should be noted that the natural frequency ($\approx$ 4.4 Hz) in the unforced flow is relatively broadband (fig.5). In order to avoid any complications associated with the broadband nature of the natural frequency, the natural frequency was forced at a relatively low level resulting in a clean peak. The best example of an ordered flow (fig. 6) is one which is forced at a single frequency near the natural roll-up frequency (4.2 Hz). The power spectrum exhibits sharp peaks at the forcing frequency and its second harmonic. The autocorrelation is a sine function. This 'locked' case is much more uniform than the natural case. The interaction of two strong frequencies (f_1 = 4.075 Hz, f_2 = 4.4 Hz) in the shear flow results in a quasiperiodic behavior as indicated by the presence of sum and difference interactions in the power spectrum, and by the strong modulation of the autocorrelation function (fig. 7). With the addition of a third frequency (f_3 = 5.0 Hz - fig. 8), the flow exhibits the randomness associated with chaotic motion. The background noise level in the power spectrum is an order of magnitude higher than the noise level of the locked case. The autocorrelation function shows no distinct periodicity. It is relatively uncorrelated. The changes in the autocorrelation functions and power spectra for the shear layer cases suggest a Ruelle-Takens-Newhouse[14] route to chaos scenario and are consistent with behavior of the wake studies of Williams-Stuber & Gharib[5]. It was more difficult to obtain a strong chaotic case in the shear layer compared to the wake. This is attributed to the existence of only one sign of vorticity in the shear layer. It is most likely that the shear layer is better able to adjust itself to the presence of three frequencies.

THE NONLINEAR DYNAMICAL ANALYSIS

Using the power spectrum as a primary diagnostic, it would appear that the three frequency cases behave chaotically. However, due to the lack of phase information from the power spectrum, further diagnostics from the field of nonlinear dynamics must be applied to the data. For this survey, a presentation of only the phase space reconstruction will be considered.

Phase Space Reconstruction. The first step in analyzing experimental data obtained from a dynamical system is to construct the phase space of the system. Given a time series of a single quantity, $U(t)$, (in the current experiment, the x - component of velocity), a reconstruction of the phase space can be obtained by using a time delay technique[14,15]. The phase portraits (phase space reconcructions) for the natural (unforced) flows and the locked and chaotic cases for the shear layer are presented in figures 9 to 11. In the transition from natural to locked flow (figs. 9 to 10), the organizing of the phase portrait is evident. Random noise is suppressed in the locked case as was seen previously in the power spectrum. The locked portrait resembles a thin cord or torus. In contrast, the chaotic phase portrait (fig. 11) resembles tangled balls of yarn rather than thin ribbons.

It should be noted that additional forms of the phase portrait can be considered if additional components of velocity are measured. For the flows studied, the transition in phase portraits was consistent regardless of the velocity component used for the reconstruction. An example of the phase space reconstruction using the shear stress $u'v'(t)$ for the locked and chaotic flows are shown in figure 12. The jaggedness of the lines is due to poor resolution in the A/D conversion of the v component of velocity.

FLUID DYNAMICS OF A CHAOTIC SHEAR FLOW

As part of a more traditional fluid mechanics analysis, the mean ($\overline{U}$)and rms ($\sqrt{\overline{u'^2}}$) velocity profiles of the locked and chaotic flows are presented in figure 13. The locked case is indicated by a solid line, the chaotic case by the symbols. Relatively little change is seen between the locked and chaotic mean profiles . The shear layer rms profiles are both double peaked which indicates a later stage of transition in the flow relative to the natural flow (not shown). The shear stress ($\overline{u'v'}$) profile and the mean cross stream velocity ($\overline{V}$) profiles for the locked and chaotic shear layers are presented in figure 14. The mean $\overline{V}$ profile shows a change in the entrainment for the locked case. The chaotic case is similar to the natural profile. The difference in the shear stress profiles profiles is due to the fact that the locked flow is at a later stage of transition. Again, the chaotic profile is similar to the natural profile.

DISCUSSION AND RESULTS -PART II
THREE DIMENSIONAL STRUCTURES

The results presented here for the study of the origin of three-dimensional structures in shear flows are power spectra and flow visualization results. The power spectra were measured at the point of discontinuity between the strips along the span at a distance of 3" from the trailing edge of the splitter plate.

When the flow is forced with the same frequency (4.0 Hz) on both strips, the power spectrum (fig. 15) shows strong peaks at the forcing frequency and its second harmonic. In essence, the flow is 'locked' to the forcing frequency. When the flow is forced at two different frequencies along the span (4.0 Hz and 4.4 Hz), the power spectrum (fig. 16) shows peaks at the forcing frequencies as well as at linear combinations of the forcing frequencies. This behavior in the power spectrum is typical of quasi-periodic behavior.

Flow visualization along the span of the shear flow was achieved by using a cavity type dye injection system. When the flow is forced with a single frequency, uniform vortex lines are observed (fig. 17). When the ratio of forcing frequencies is 2:3, a simple branching structure is seen (fig. 18). As the ratio of forcing frequencies approaches 1:1, the vortex reconnection becomes more complex (fig. 19). Video tapes of the vortex reconnection process shows a helical reconnection vortex along the discontinuity when the two forcing frequencies are similar.

SUMMARY OF RESULTS

This study has explored the response of shear layers to multi-frequency forcing. In the presence of three frequencies, the flows exhibit chaotic behavior. It is interesting to note that even though the inputs to the system are known (three distinct waves), the "controlled" system behaves randomly. In addition, the generation of three-dimensional structures in shear flows as a result of frequency variation along the span of the flow is presented.

Even though a variety of fluid behaviors has been presented in this report, there remains much to be understood about the chaotic and three dimensional flows. One additional area of exploration would be to relate the stability characteristics of the flows to the observed behaviors. It is hoped that this approach wouldprovide more insight into the vortex reconnection behavior. Another question still be examined is the effect of chaotic and quasiperiodic behavior on the growth rate of the shear layers.

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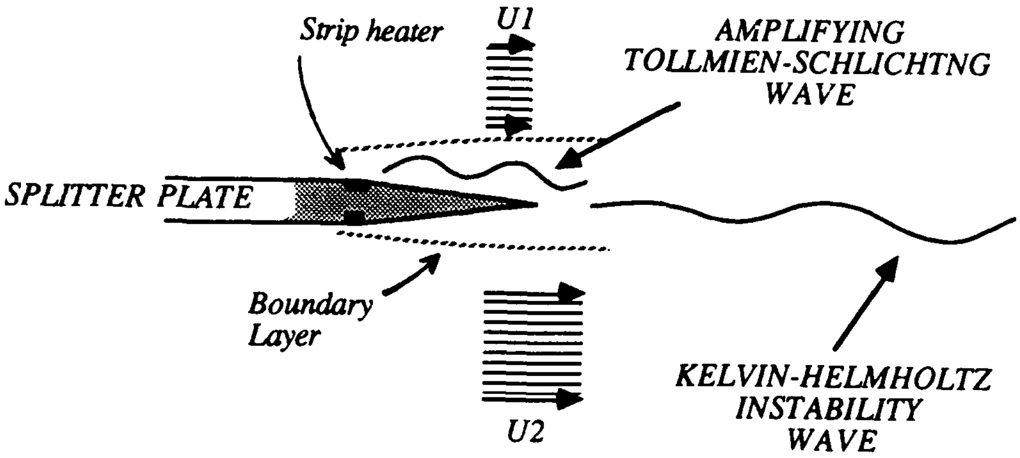


Figure 1 - Strip heater technique for forcing shear flows

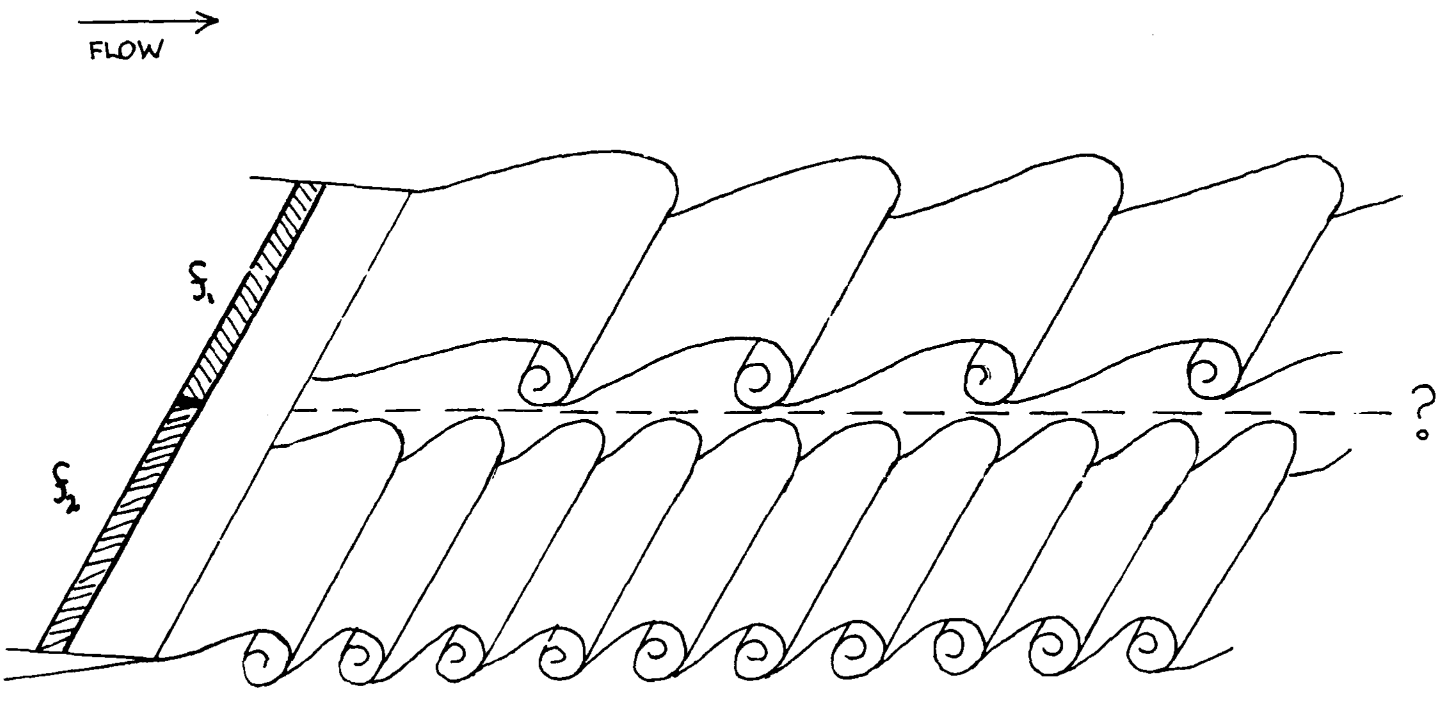


Figure 2 - Strip heater configuration for creating a spatial variation of frequency across the mixing layer

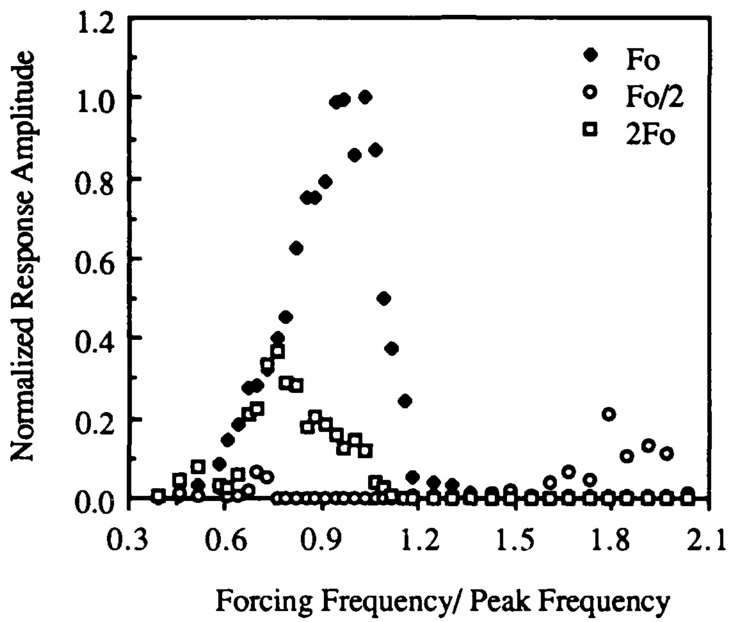


Figure 3 - Shear layer response to external forcing

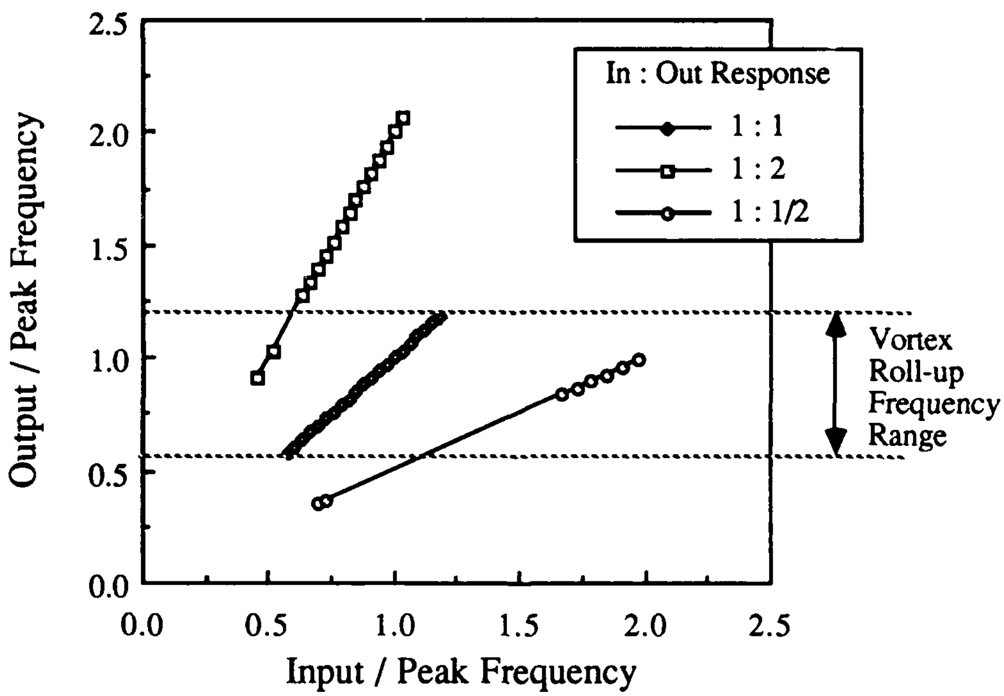


Figure 4 - Shear layer frequency response diagram

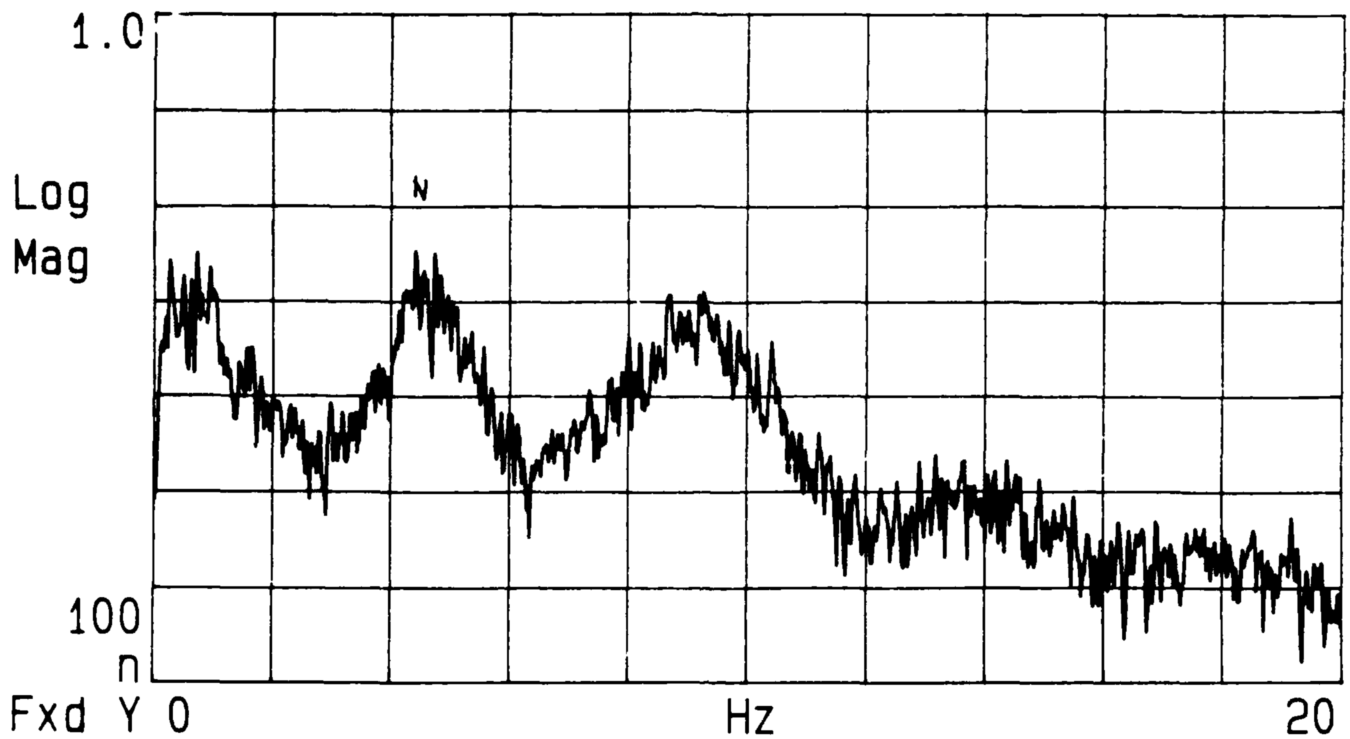


Figure 5 - Power spectrum for the natural mixing layer

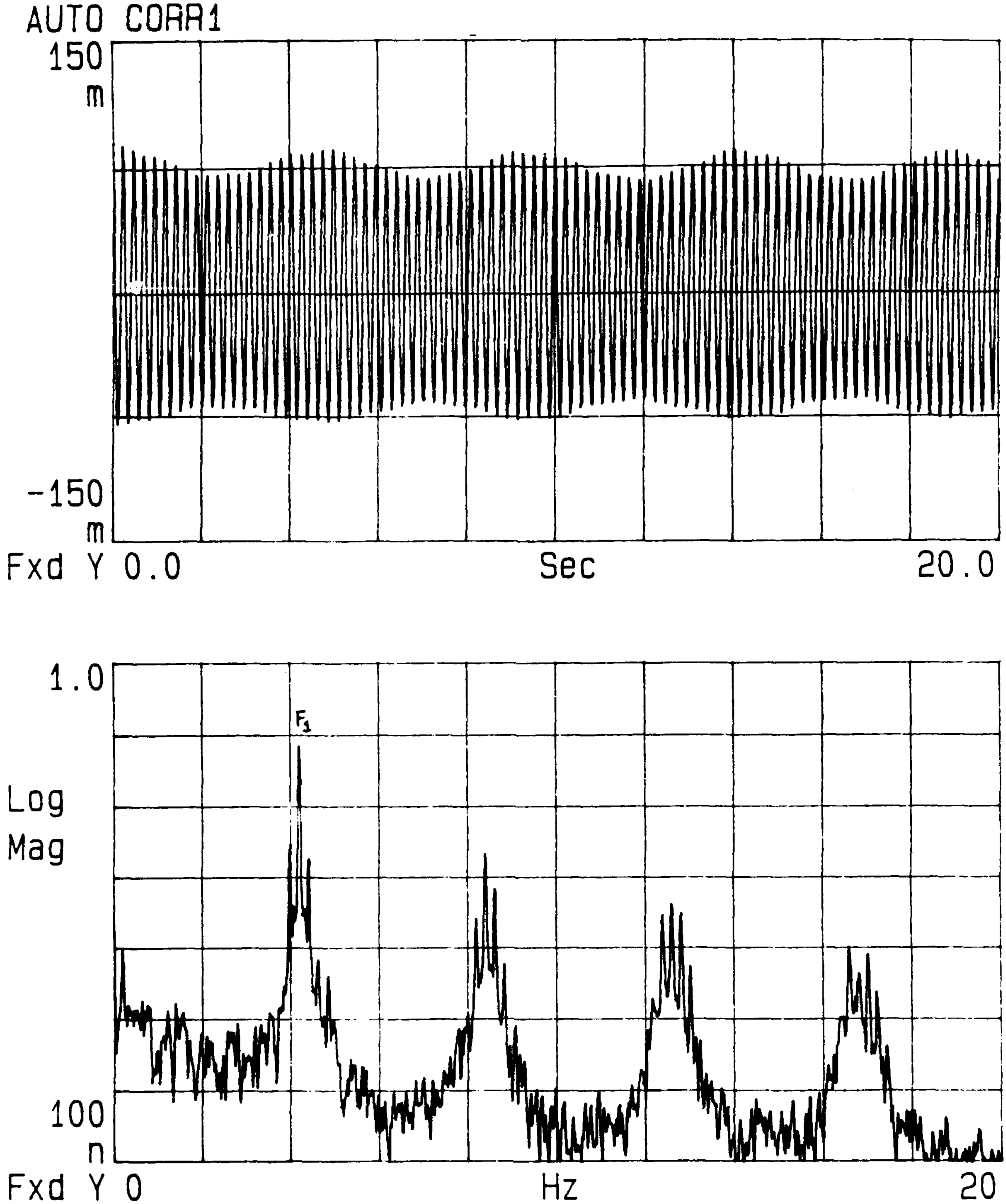


Figure 6 - Autocorrelation function and power spectrum for the locked mixing layer

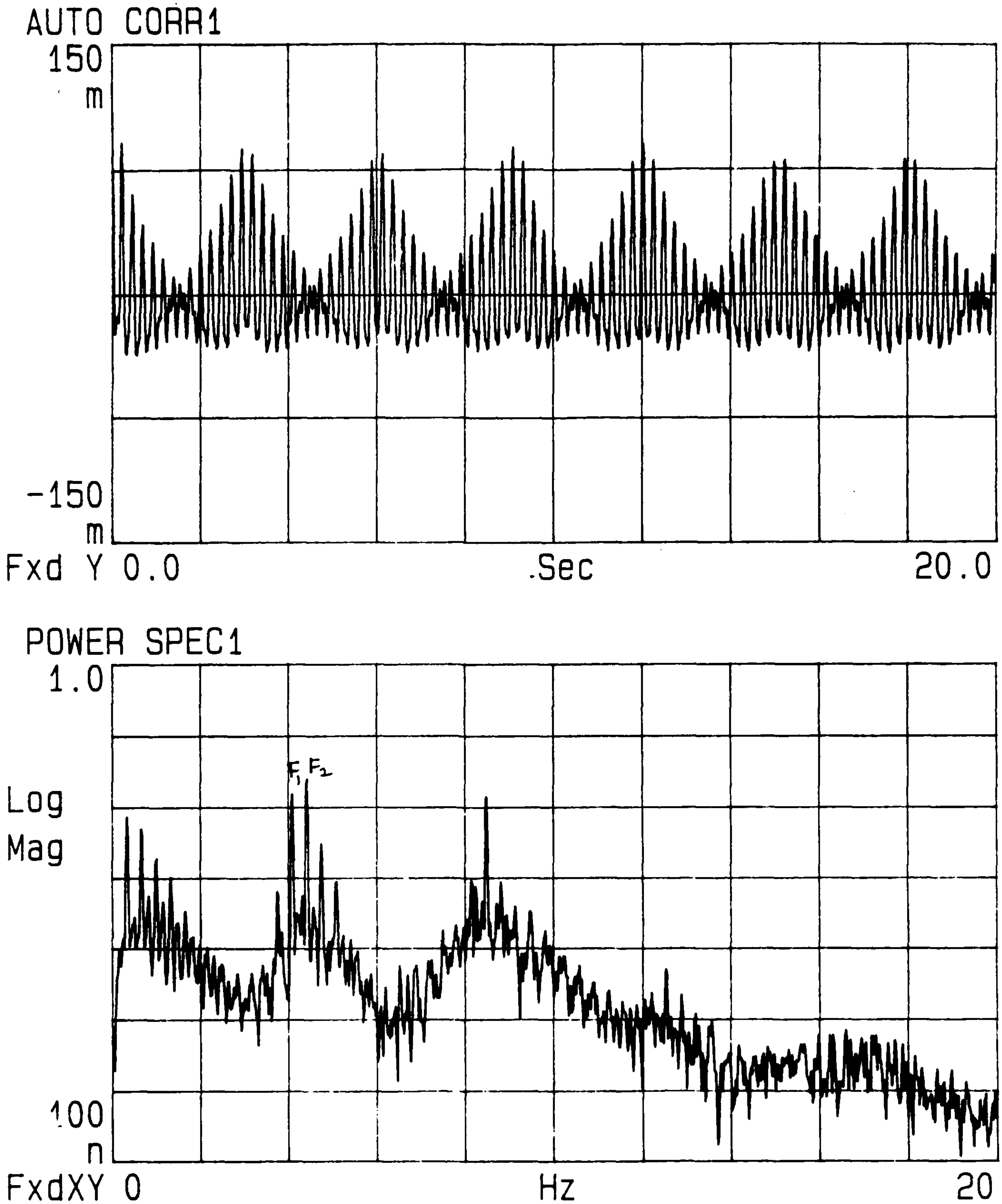


Figure 7 - Autocorrelation function and power spectrum for the quasiperiodic mixing layer

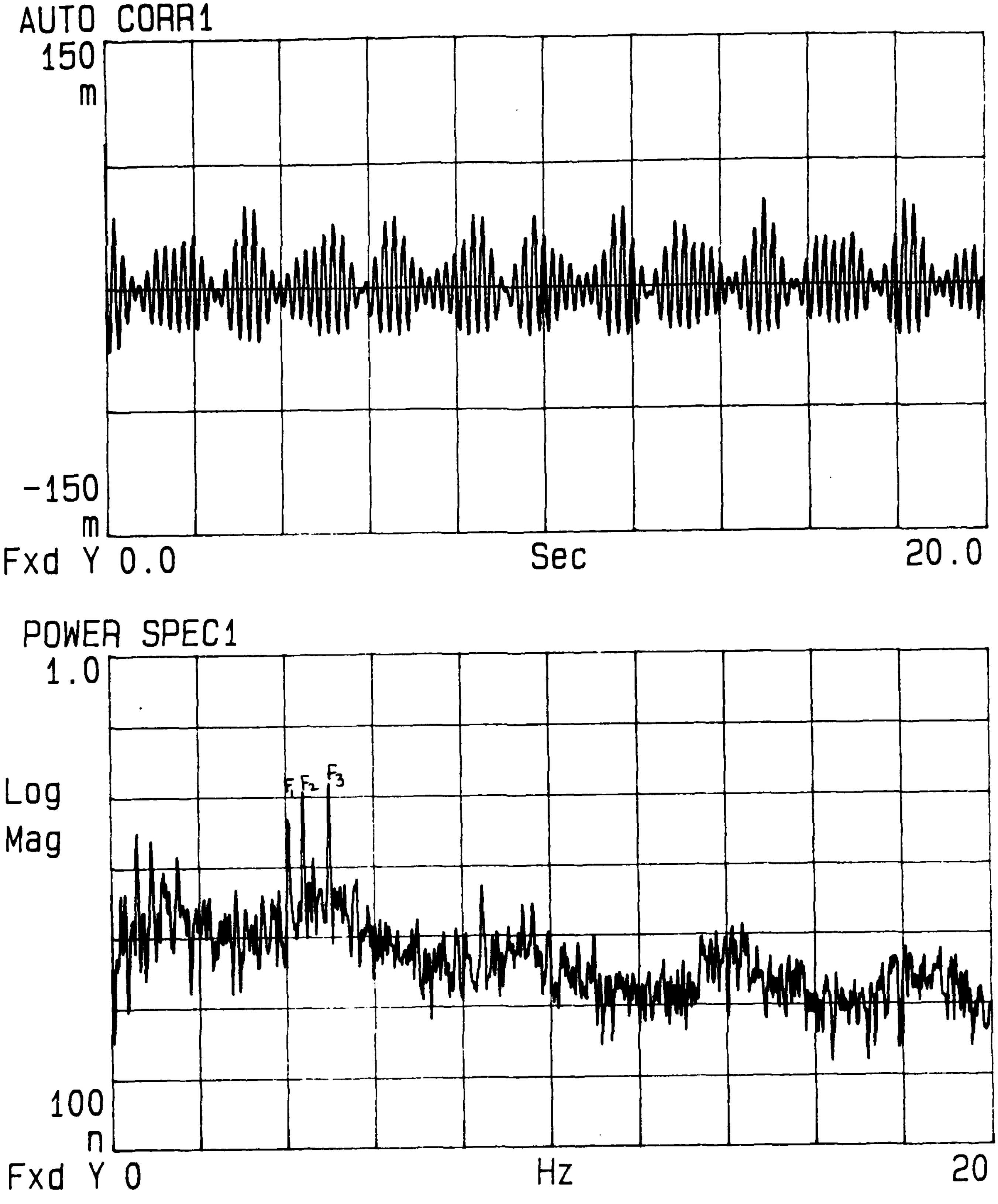


Figure 8 - Autocorrelation function and power spectrum for the chaotic mixing layer

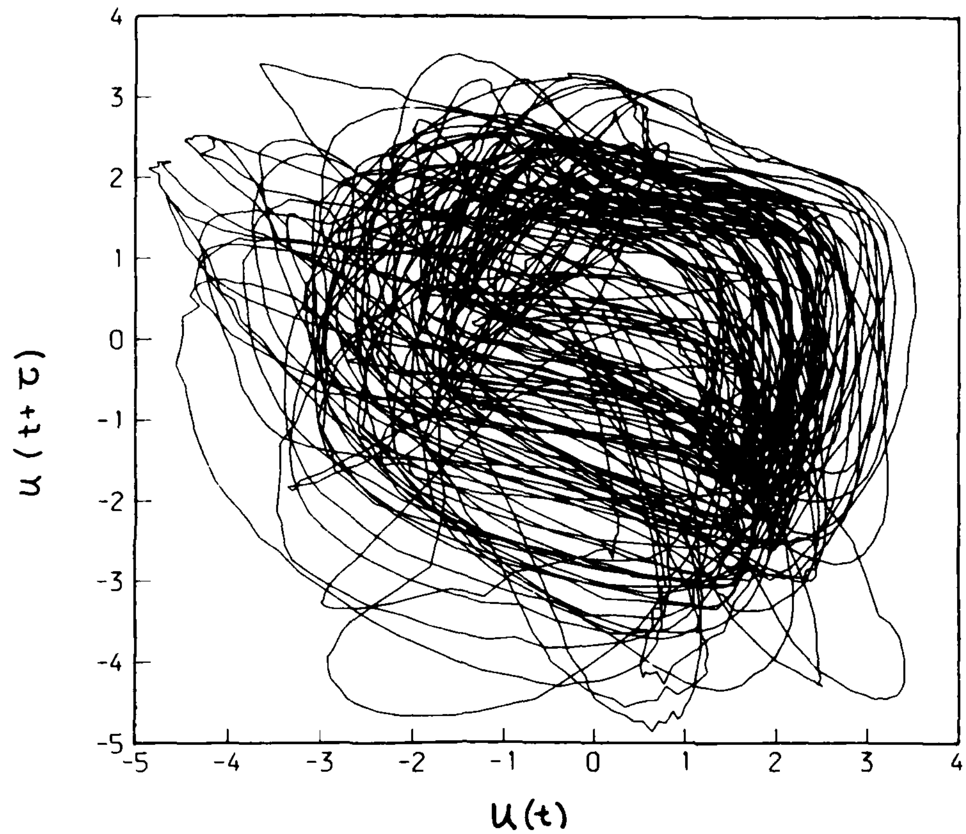


Figure 9 - Phase portrait for the natural shear layer

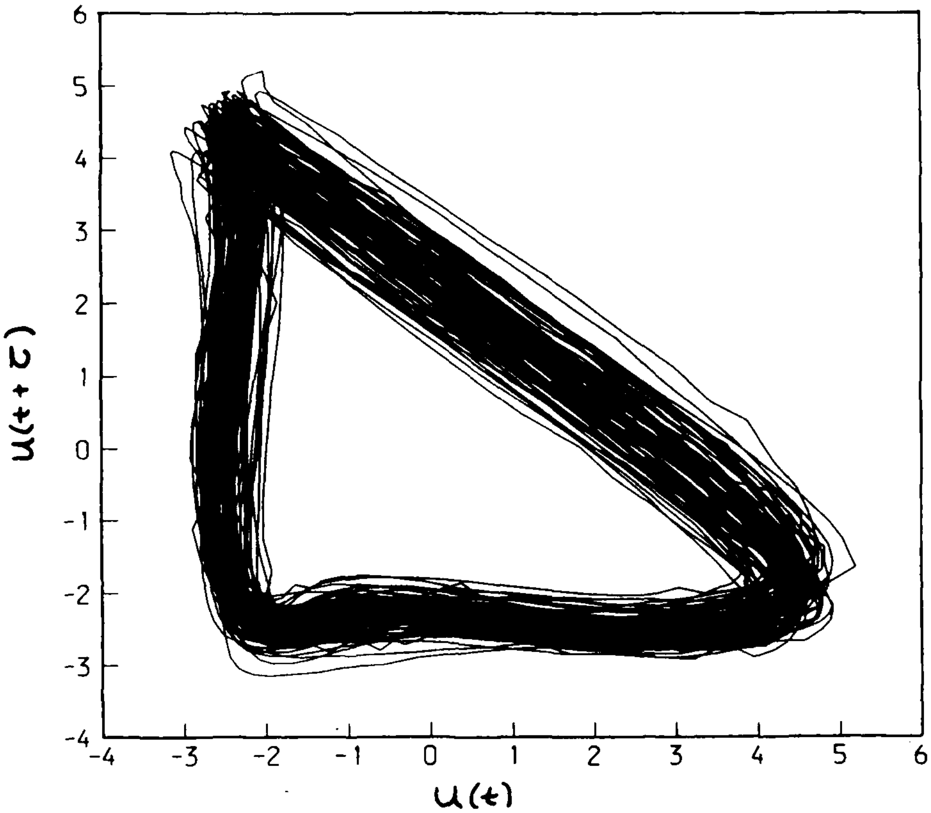


Figure 10 - Phase portrait for the locked shear layer

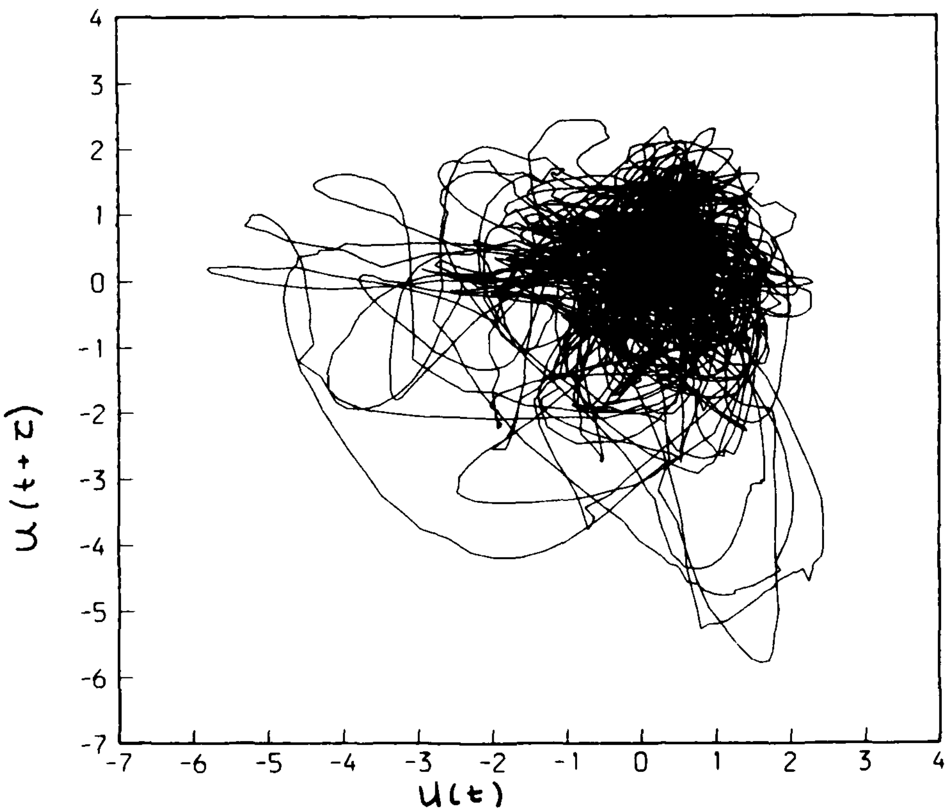
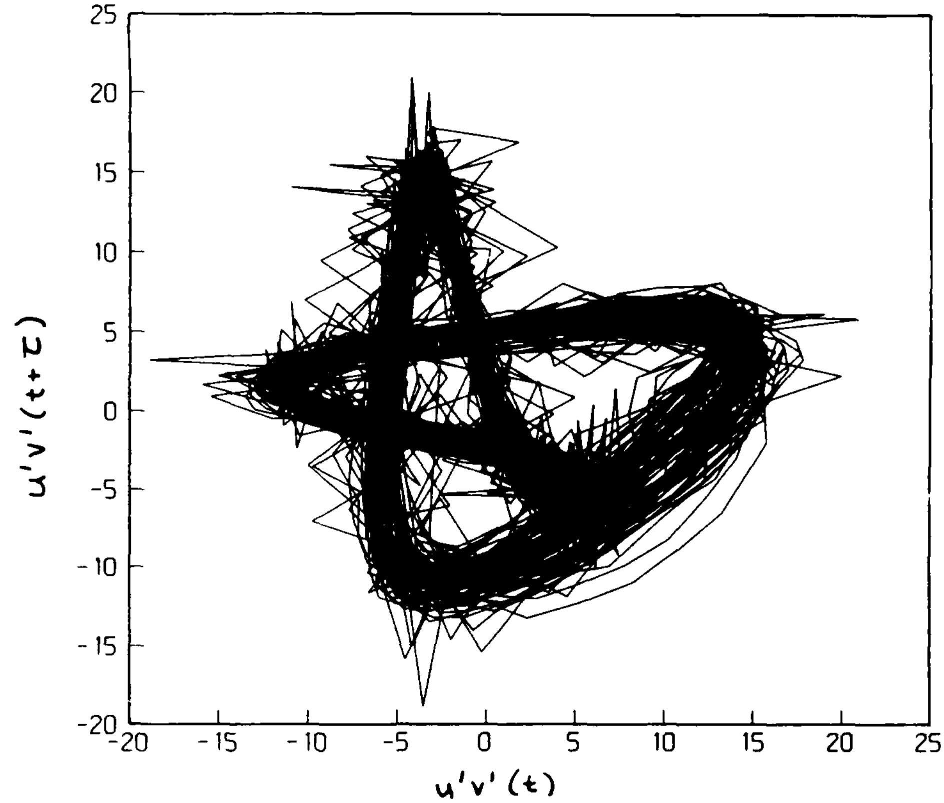


Figure 11 - Phase portrait for the chaotic shear layer

(A)



(B)

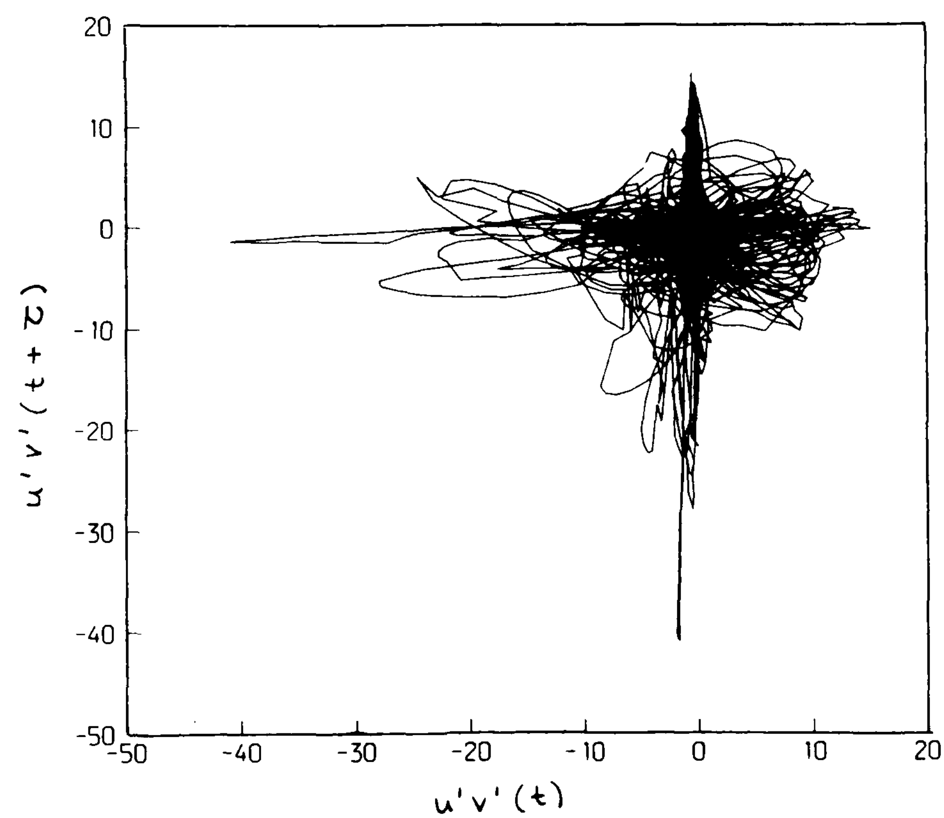


Figure 12 - Phase portraits for shear layer using $u'v'(t)$ for the reconstruction
(A) Locked (B) Chaotic

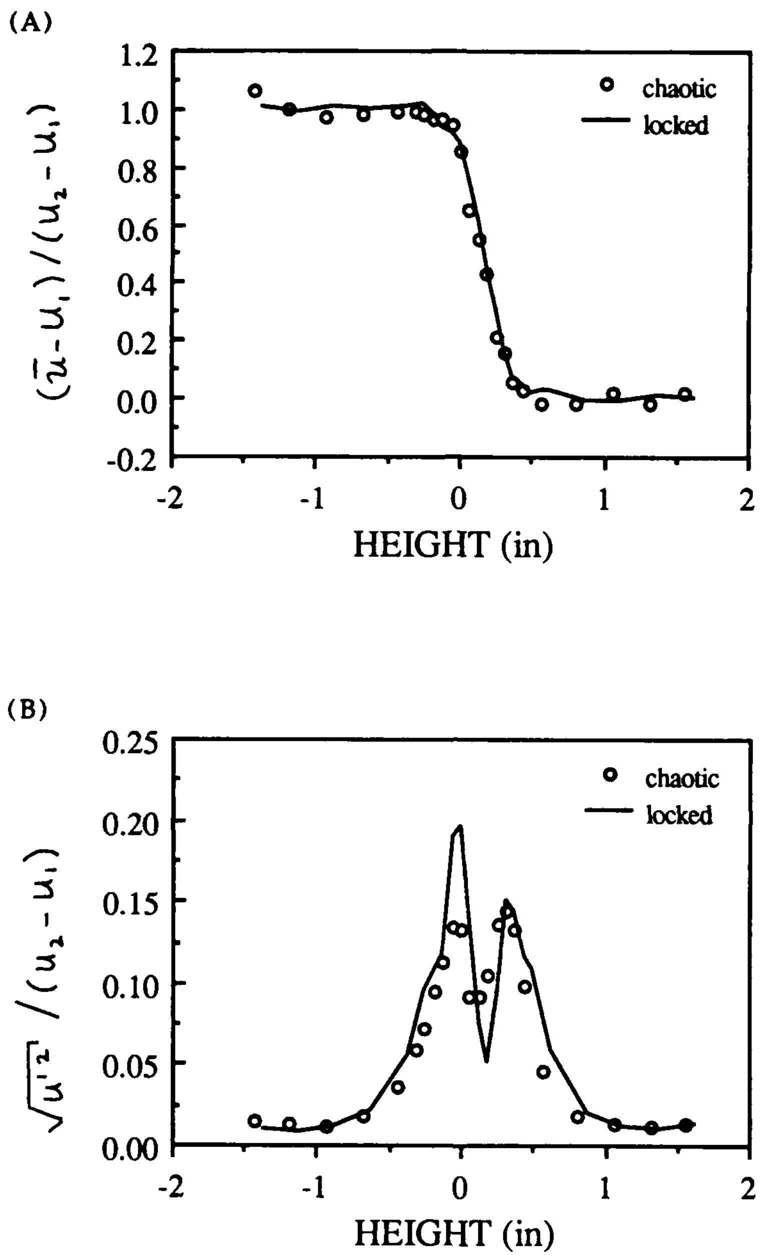


Figure 13 - Mean and rms velocity profiles for locked and chaotic shear layer

(A) U component of velocity

(B) Rms velocity (u')

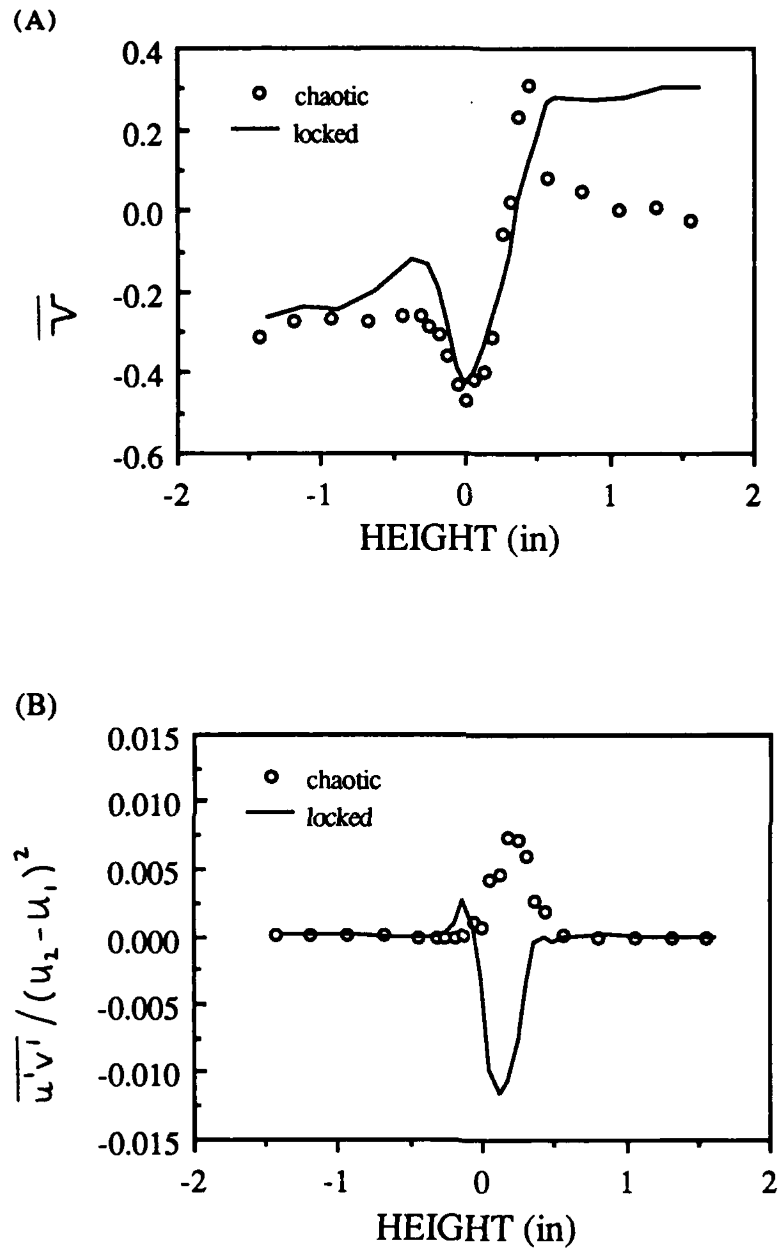


Figure 14 - Velocity profiles for locked and chaotic mixing layer

(A) V component of velocity

(B) Reynolds stress $(\overline{u'v'})$

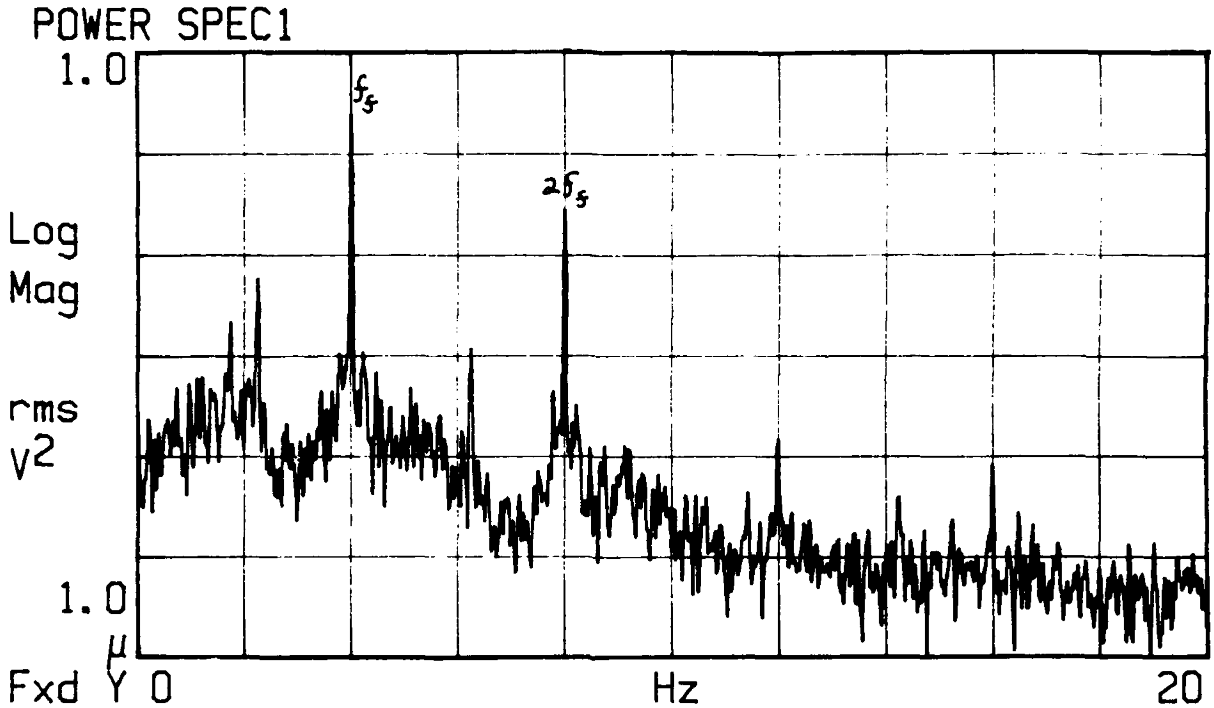


Figure 15 - Power spectrum of shear layer forced with a single frequency (4.0 Hz) across its span

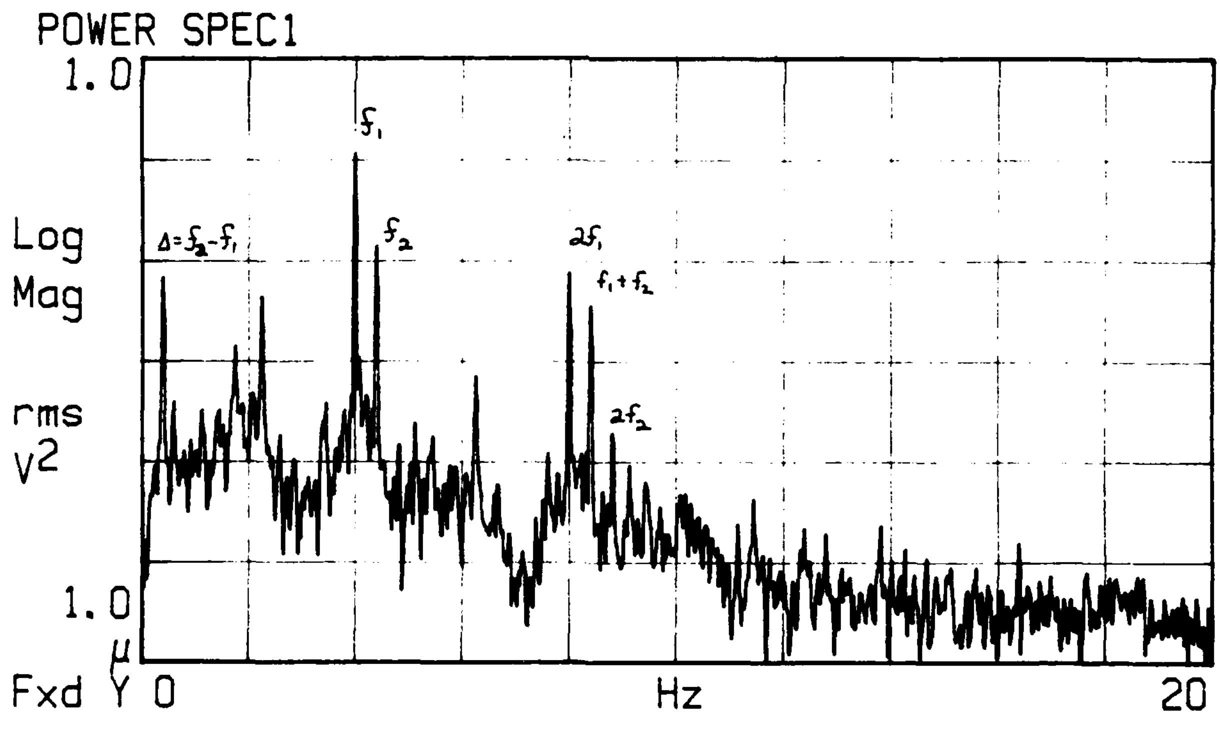


Figure 16 - Power spectrum of shear layer forced with two frequencies (4.0 Hz and 4.4 Hz) across its span

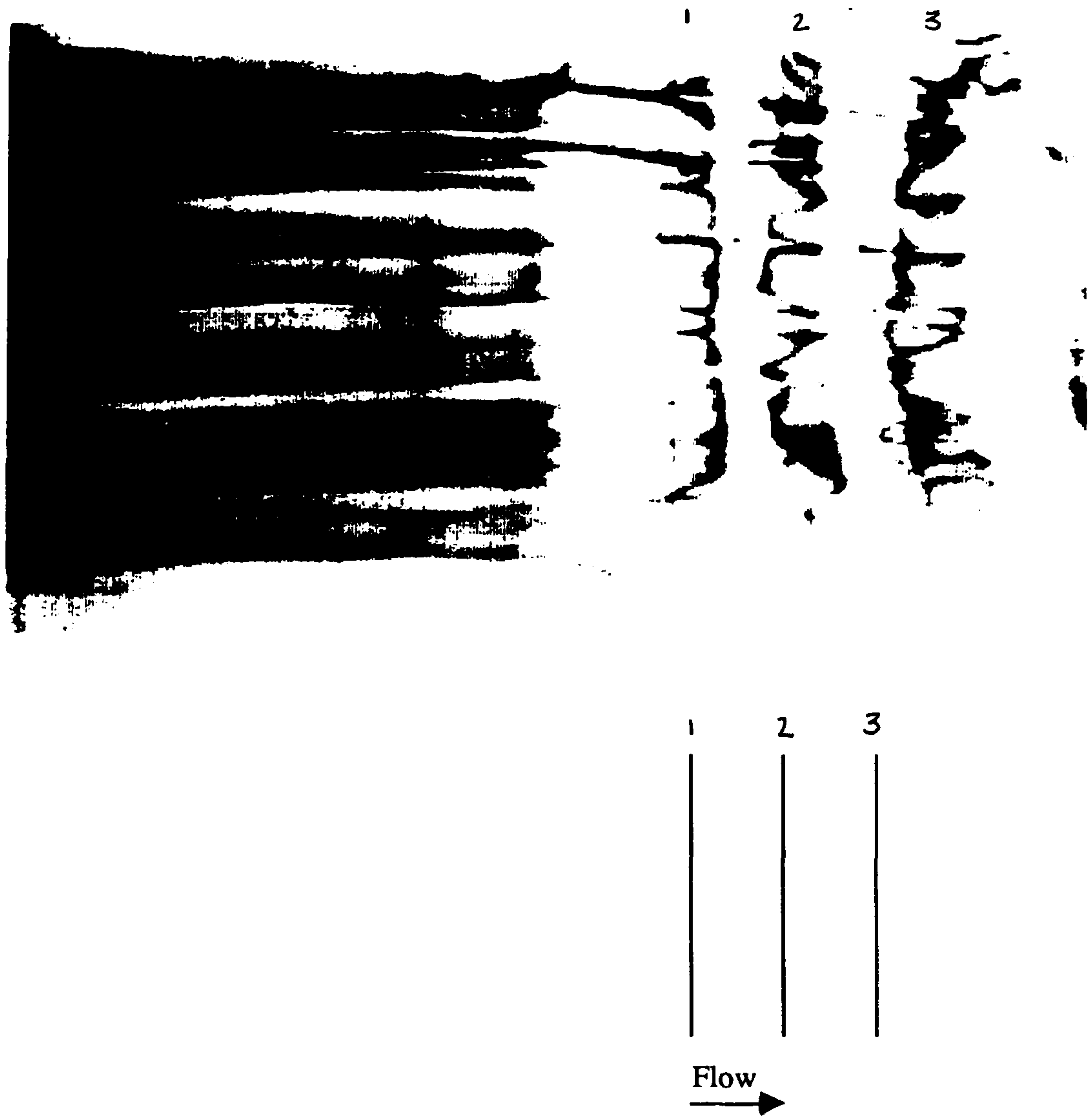


Figure 17 - Flow visualization and schematic of natural flow

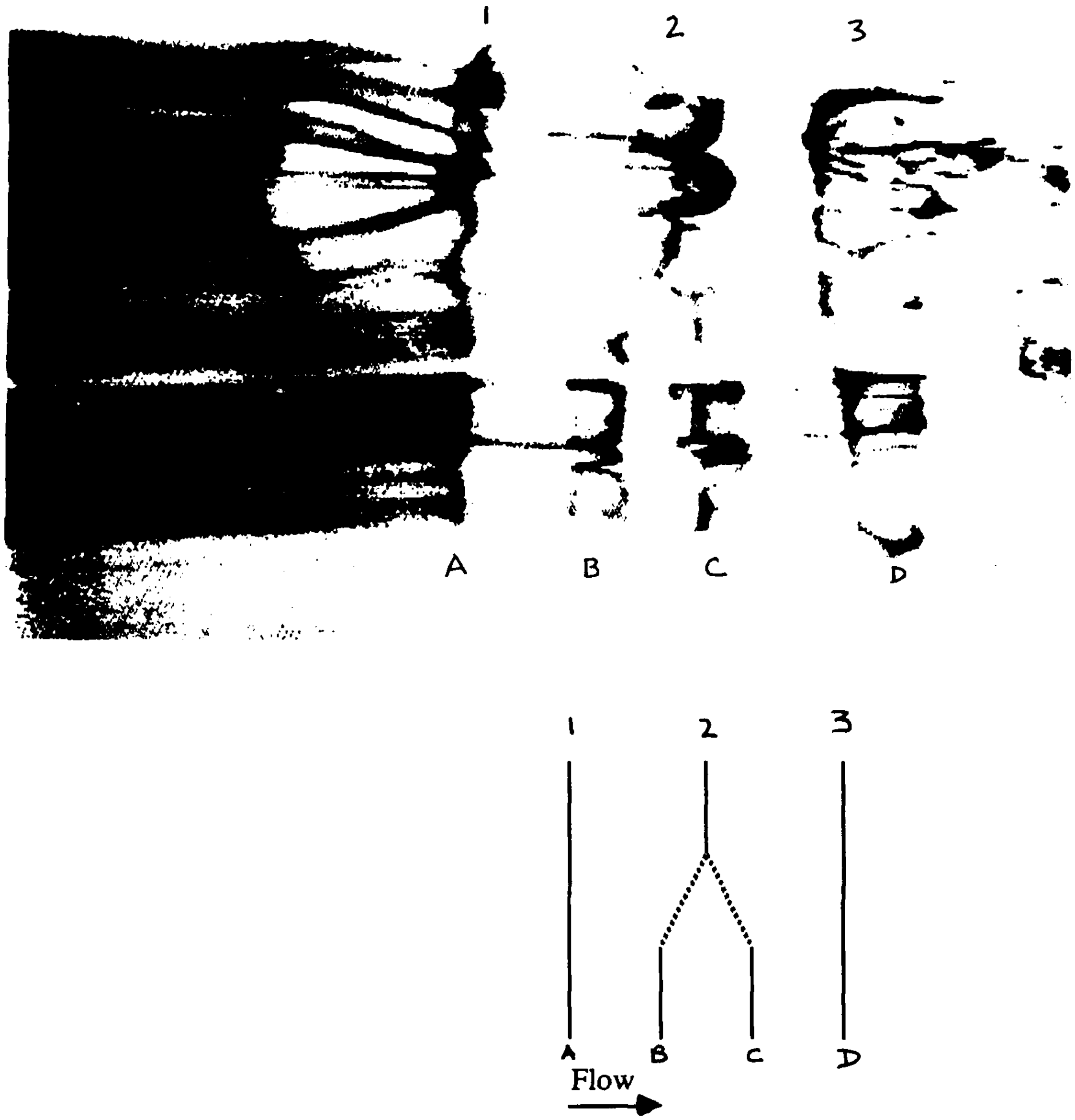


Figure 18 - Flow visualization and schematic of flow forced with two frequencies in a ratio of 2 : 3

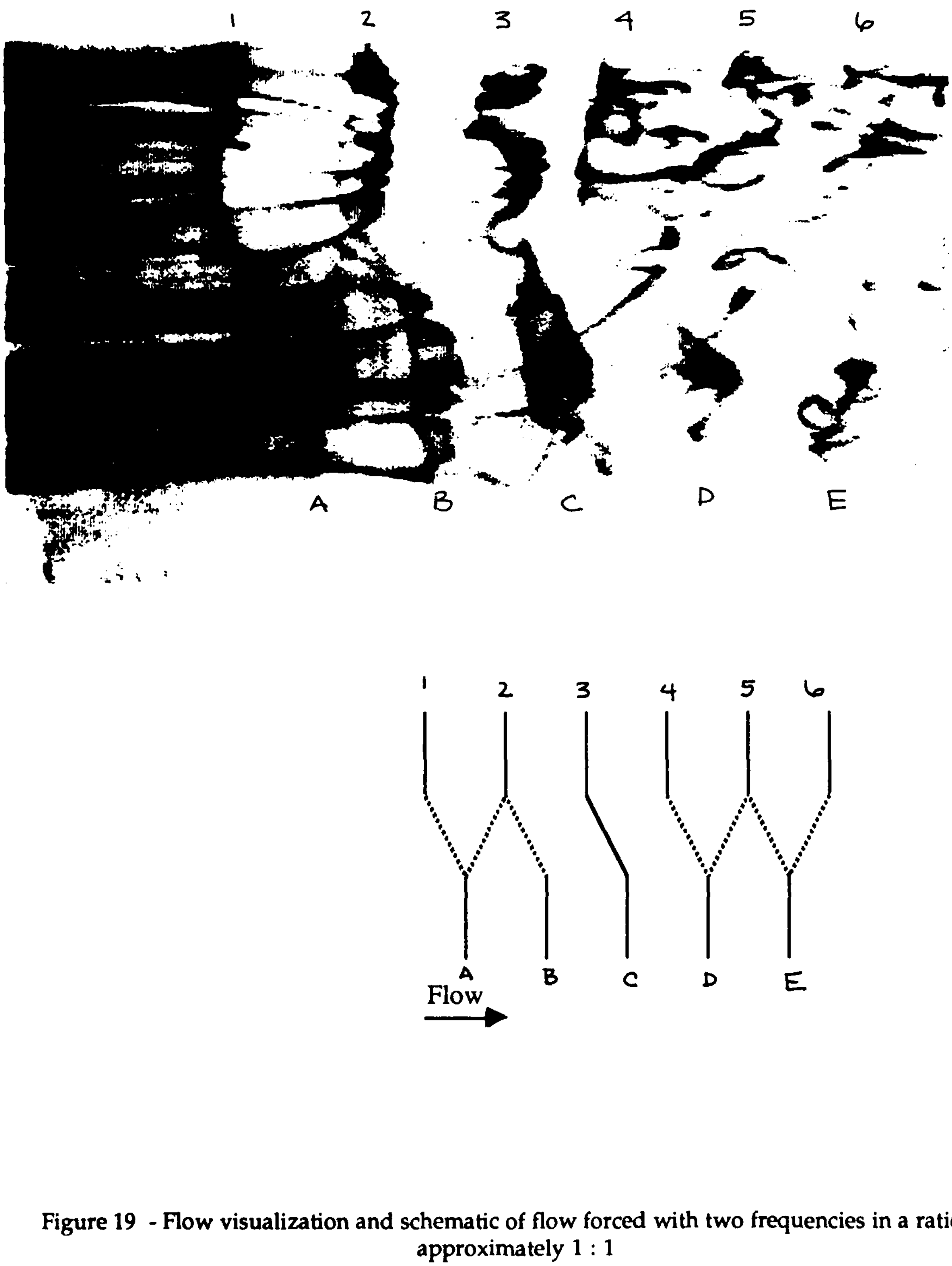


Figure 19 - Flow visualization and schematic of flow forced with two frequencies in a ratio of approximately 1 : 1